DEVELOPMENT OF AN ELECTRONICALLY-SCANNED PRESSURE MODULE FOR OPERATION AT CRYOGENIC TEMPERATURES

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DEVELOPMENT OF AN ELECTRONICALLY-SCANNED PRESSURE MODULE FOR OPERATION AT CRYOGENIC TEMPERATURES

By

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SUMMARY

Pressure and temperature characteristics were measured for a number of multichannel electronically scanned pressure sensors. The tests were made on commercially available units which were designed to operate in a controlled temperature environment. Measurements of zero shift, sensitivity, and nonlinearity for each transducer were taken over a temperature range from 100 K to 340 K using a computer controlled data acquisition system.

The units tested failed to meet accuracy specifications over the complete temperature range, whicn was expected. However, the sensors showed acceptable and predictable behavior over the temperature range from approximately -40° C (233 K) to 70° C (343 K). It was determined tnat a combination of local neating and accurate temperature monitoring can result in a device tnat can be compensated for temperature as well as its otner physical properties. The design of a prototype for operation in a cryogenic environment is proposed, and a metnod for compensation is developed.

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TABLE OF CONTENTS

LIST OF FIGURES

TABLE OF CONTENTS - concluded

LIST OF FIGURES - concluded

INTRODUCTION

For the past several years, electronically-scanned pressure (ESP) transducers have been used to make multichannel pressure measurements in the wind tunnels at the NASA Langley Research Center (Ref. 1). A typical ESP module consists of a series of pressure sensors, a multiplexer for scanning the outputs of the sensors, and an amplifier to condition the outputs for transmission to a data acquisition system external to the test environment (Ref. 2). Most of these measurements have been made under moderate environmental conditions and meeting accuracy requirements has not been overly difficult to achieve. However, since the cryogenic windtunnel, the National Transonic Facility (NTF), has been put into operation, pressure measurements have been required at temperatures approaching that of liquid nitrogen. Since the commercially available ESP modules are designed to operate at temperatures only down to -18 degrees Celsius, it is necessary to place them in heated enclosures. Furthermore, accuracy specifications required that the temperature of the enclosures be nignly controlled to reduce parameter variations. The requirement for heated enclosures results in a rather bulky measurement system wnich is very difficult and sometimes impossible to build into a scaled-down module. Therefore, in many cases, the modules in their heated enclosures are placed in the tunnel external to tne model and pressure tubing is connected from the model to the module. Since hundreds of pressure measurements may be required, the system often becomes unwieldy and difficult to connect and maintain. In such cases, even relatively simple problems can take hours or days to locate and correct.

The goal of this research was to develop a measurement system to reduce or eliminate most of these limitations without compromising the integrity of the measurements. The approach decided upon was to measure the properties

of the transducer as a function of temperature and pressure and provide compensation as the thermal environment of the transducer is allowed to change. Three major problems which had to be addressed were: The accurate determination of the thermal behavior of the sensors; The precise measurement of sensor temperature for accurate compensation of the measurement; and a method of incorporating the additional temperature sensors into the module with a minimum effect on size and channel capacity. Of lesser importance was the problem of operating the multiplexer and instrumentation amplifier at low temperatures. This was not perceived as a major problem since comprehensive studies (Ref. 3) have shown that a great number of standard off-the-shelf electronic components can be operated reliably down to liquid nitrogen temperatures.

The pressure transducers used in the ESP modules are fabricated by diffusing into a silicon diaphragm a Wheatstone bridge consisting of piezoresistive elements (Ref. 4). The pressure tubing is then connected to the diaphragm such that the piezoresistive bridge elements are stressed under pressure. With a constant voltage placed across the input to the bridge, the change of resistance under pressure results in a change of voltage at the bridge output terminals. The output voltage as a function of pressure is approximately linear and exhibits a small offset voltage at zero pressure. It has been found tnat the small nonlinearity that exists can be represented to a high degree of accuracy by a quadratic approximation. All of these properties are affected by temperature. The following equation relates the pressure, P, to the bridge output voltage, V:

$$P(T) = C1(T) + C2(T)V + C3(T)V^2$$

where   C1(T)   is the offset pressure, as a function of
temperature, required to yield zero output
voltage from the bridge,

C2(T)   is the linear coefficient, as a function of
temperature, also called sensitivity,

and   C3(T)   is the nonlinear coefficient, as a function
of temperature.

If the tranducer is to be operated in a controlled thermal environment (for example, room temperature), then the temperature variation of the coefficients is eliminated and the calibration procedure becomes relatively simple. One nas only to apply three known pressures and solve tnree equations for three unknowns. If the transducer is now operated at the same temperature as the calioration temperature (assuming repeatability), then the pressure can be calculated accurately from the output voltage. This calibration can actually be performed on-line between data taking events.

If the temperature is allowed to vary, however, the calibration procedure becomes much more complicated. In this case, the temperature behavior of the coefficients for each transducer must be determined in advance and stored in the computer. This procedure requires off-line calibration using an environmental chamber and the accurate measurement of temperature as well as voltage and pressure. In actual operation, two output voltages for each channel are read into the computer. One of the voltages is derived from a temperature sensor and the other is taken directly across tne oridge output terminals and is proportional to pressure as well as temperature.

The temperature sensors are placed as close to the pressure transducers as possible in order to minimize the effects of temperature gradients. A block diagram for tne proposed model is shown in Fig. 1. This module will have one temperature sensor for each channel. However, it may be possible in future models to use fewer temperature sensors oy strategically placing them on the substrate and using thermal analysis to calculate the temperature of each pressure sensor.

EXPERIMENTAL PROCEDURE AND RESULTS

The ESP modules used in the experimental phase of this research were composed of 32 solid-state pressure transducers, a multiplexer to scan each sensor in turn at a rate of up to 20,000 times a second, and an instrumentation amplifier to condition tne output signals before transmitting them to the data acquisition system. The schematic diagram of a commercially available 32 channel module is snown in Fig. 2. This module is composed of two sub-units: an alumina $(AL_2 O_3)$ substrate which contains the pressure sensors and tne address multiplexers; and a printed circuit board containing an address decoder and an instrumentation amplifier. Several different modules and module sub-units were tested. The initial module tested was a unit (S/N 32626) nicknamed the "spider" because of its unique arrangement of pressure port tubing. During the course of the investigation, the "spider" module was needed for incorporation into a model at NTF and it became necessary to obtain an alternate unit to test. A similar 32 channel with a cracked substrate was used. The transducers were still electronically operational even though they could not be pressurized. This unit (referred to as ESP-X) was used to determine zero pressure offset data and further verify the results obtained during the testing of the "spider" module. Also tested was a
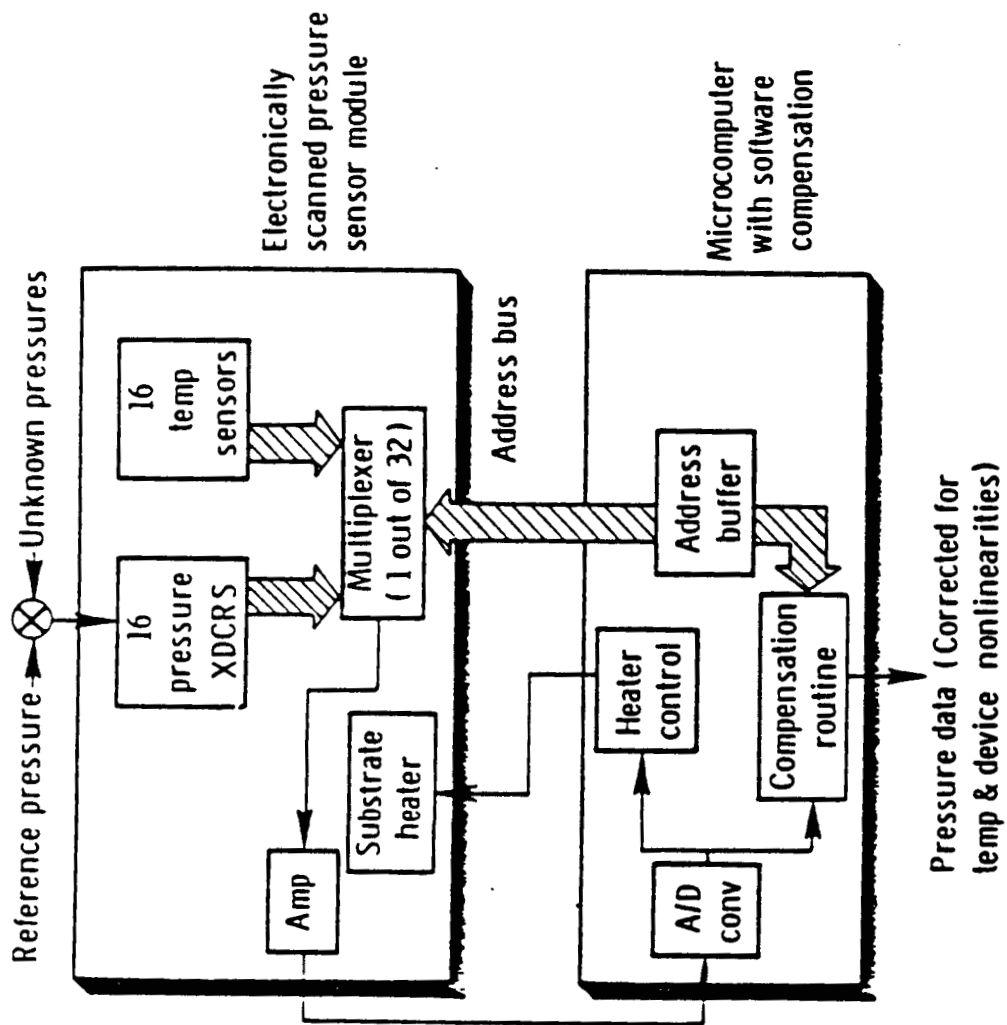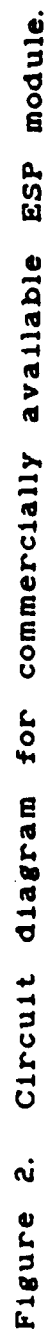
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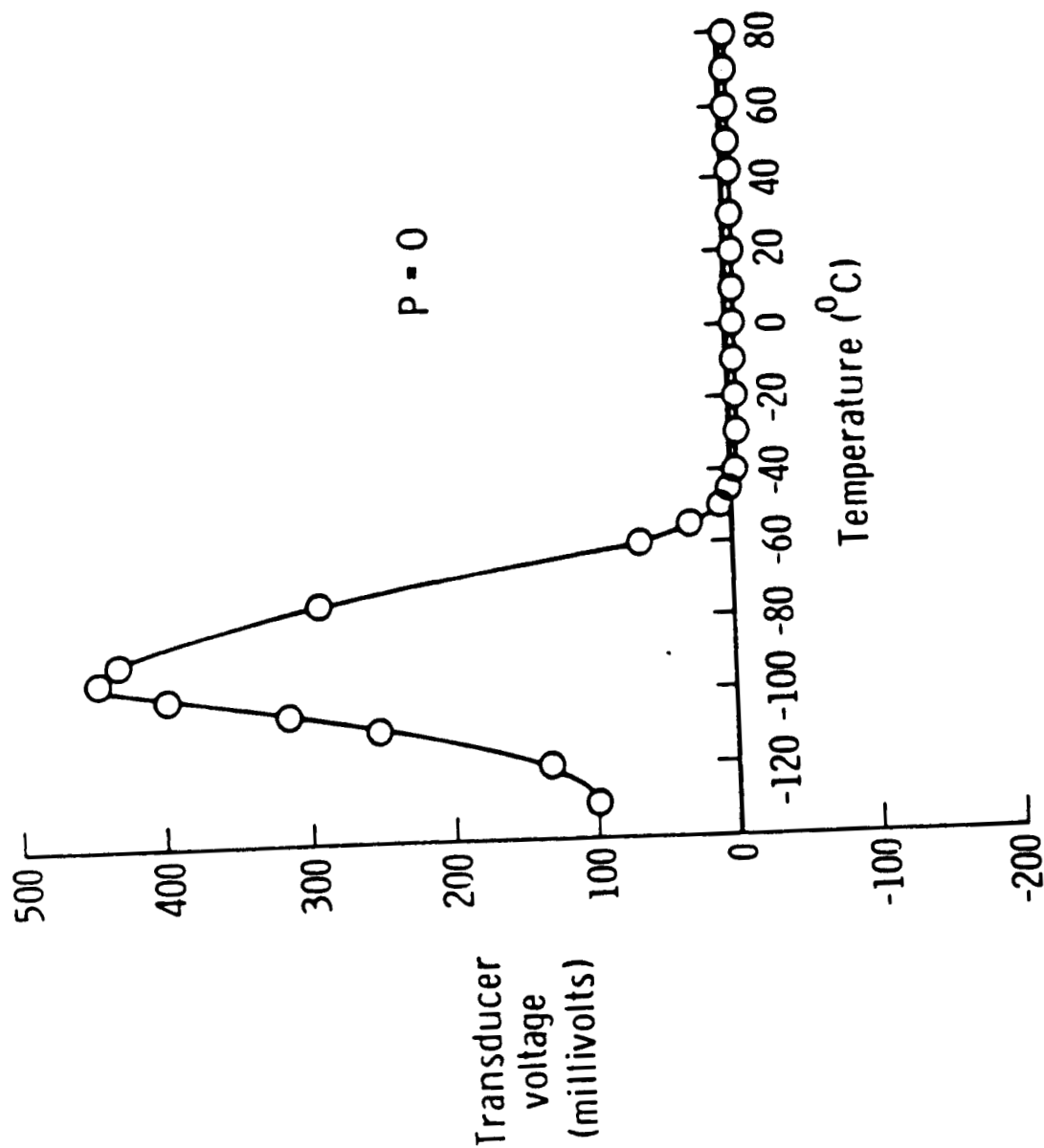Figure 1. Block diagram of proposed ESP module.

Figure 2. Circuit diagram for commercially available ESP module.

6

Figure 4. Average offset voltage as a function of temperature for ESP-X module.

7,8

sensor which has a completely different type of physical construction was subjected to the same testing to determine if it also exhibited the same properties. As can be seen in Fig. 5, this device does indeed behave in an almost identical manner. Since all sensors tested showed more or less the same problem behavior at approximately -40° C, this will be considered the lowest practical operating temperature for the proposed system.

Data were also taken which allowed the determination of the error in the pressure readings from the sensors as a function of the applied pressure over the temperature range. The plots in Figs. 6 and 7 show these errors at temperatures of -80° C, +60° C and +80° C. It is rather unexpected that the error at very low temperatures is much less than that at high temperatures. It was observed that below approximately -40° C, the large increase in sensor output (see Fig. 4) caused the output amplifier to saturate so that operation of the transducers at temperatures below -40° C was impractical. All three plots show that the negative pressure side results in a smaller error than the positive pressure side. The reason is that the calibration pressure is a positive pressure applied to the reference port which has the net effect of applying a negative pressure to the input pressure ports. The important point to be noted is that the semiconductor transducers are not symmetrical about the zero pressure axis and the calibration fails to adequately compensate when the applied pressure flexes the diaphragm in an opposite direction than did the calibration pressure. The indication here is that a new compensation technique may be in order where both positive and negative pressures are used for calibration.

Determination of C_1, C_2, and C_3 as a Function of Temperature

A more detailed analysis of the data resulted in the determination of the values of C_1, C_2, and C_3 as a function of temperature averaged

10
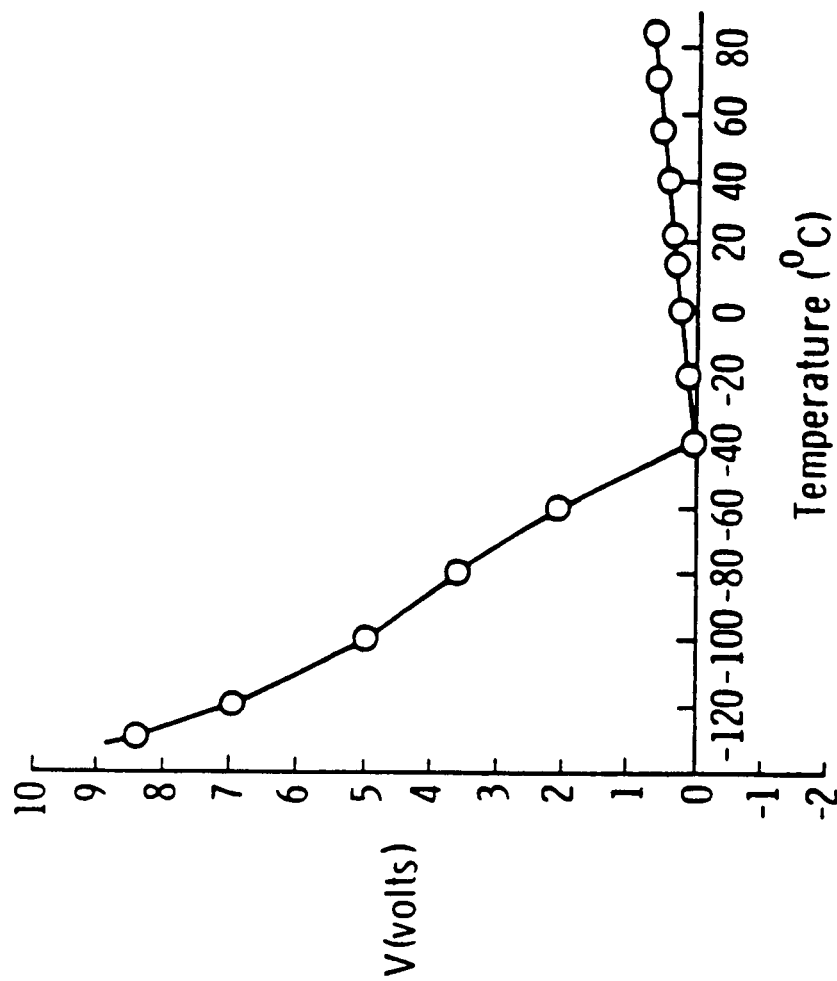
Figure 5. Zero offset voltage as a function of temperature for a single-channel sensor.

Uncalibrated side

Calibrated side

$\overline{\Delta P} = \overline{P}_{reading} - P_{applied}$ (PSI)

Applied pressure (psi)

T = -80°C

+.15% F.S. error bounds

.10
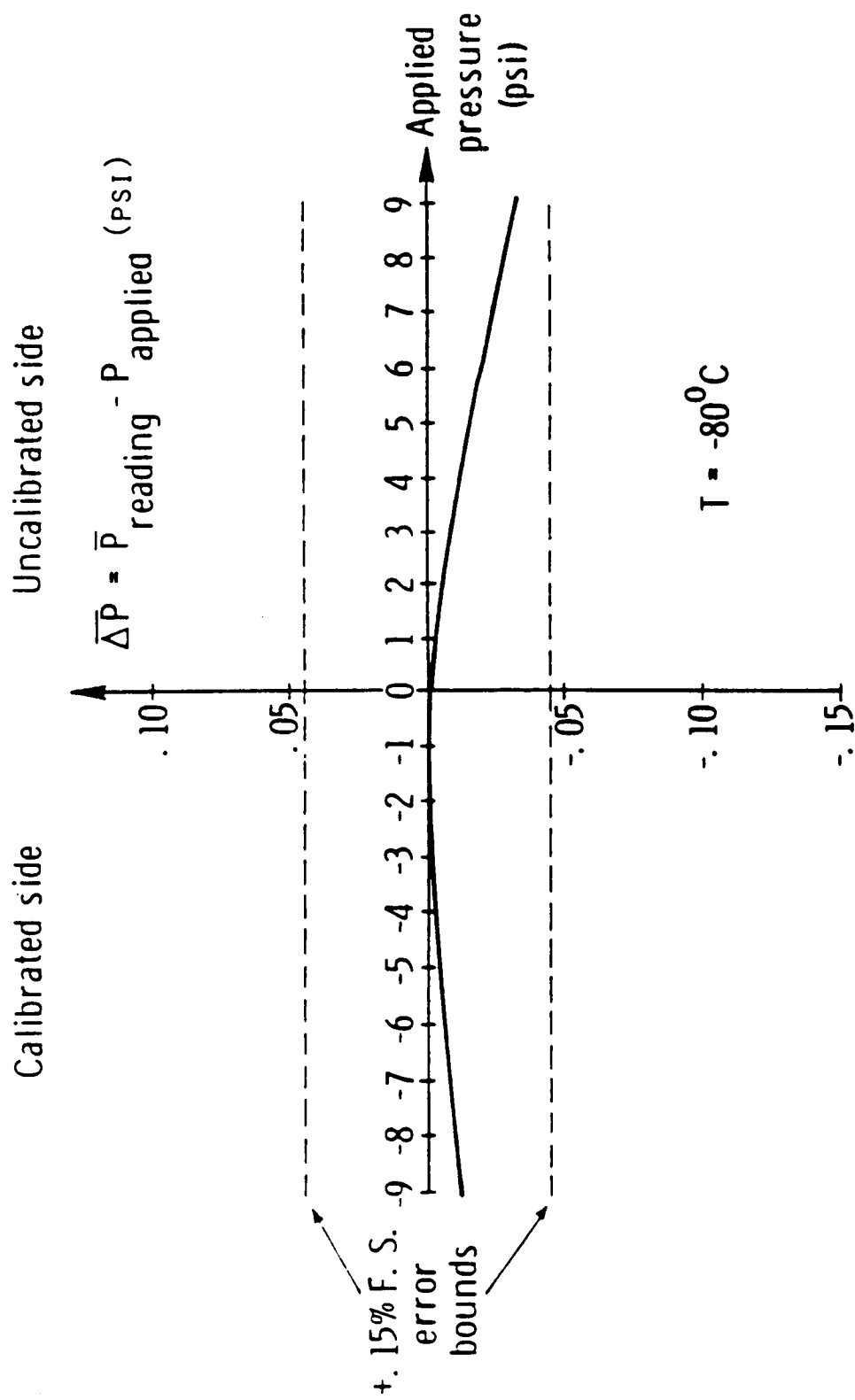.05
0
-.05
-.10
-.15

-9 -8 -7 -6 -5 -4 -3 -2 -1   1 2 3 4 5 6 7 8 9

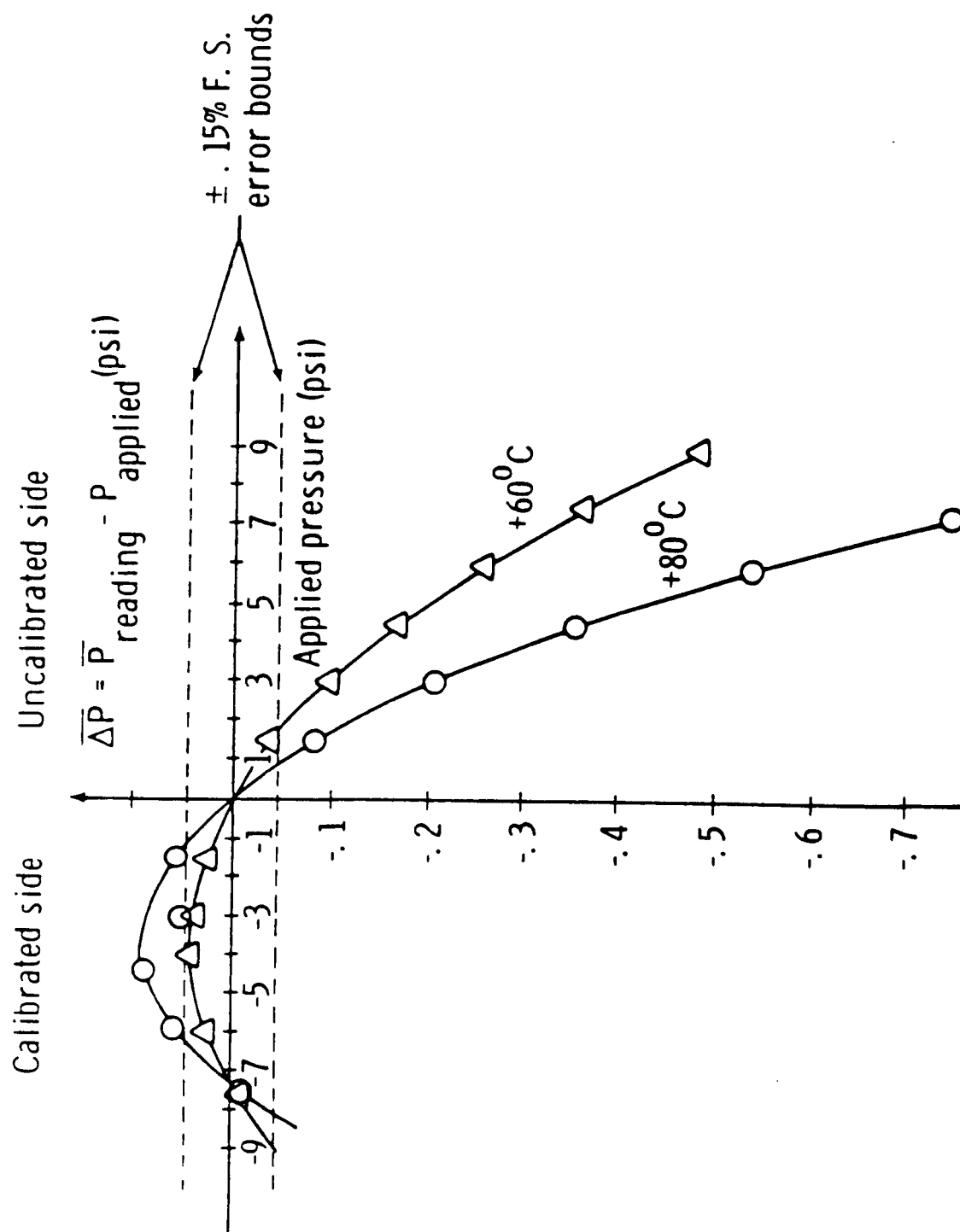Figure 6.   Average error in pressure reading as a function of applied pressure for "spider" module at T = -80° C.

Figure 7. Average error in pressure reading as a function of applied pressure for "spider" module at T = 60° C and 80° C.

over 16 channels (a malfunction in the address lines resulted in the first 16 channels being addressed twice). Figures 8, 9 and 10 show the plots of these coefficients as a function of temperature. As can be seen from these plots, the practical working range of temperatures where the behavior is reasonably well defined is from about +50° C to about -40° C. This is a rather restricted range of operation and requires some modification of the original objective of operating the sensors directly in the the cryogenic environment. Namely, it appears that a certain amount of local heating must be provided to keep the sensors above -40° C. The actual control of the temperature above -40° C is not as important as its precise measurement since the temperature behavior of the coefficients is known. It should be pointed out that, even though the plots in Figs. 8, 9 and 10 are for 16 channels averaged together, each individual channel snowed similar characteristics.

Example Case

As an example of the compensation technique, the following coefficients for channel 1 of the "spider" module were obtained from the data by using simple linear regression:

$$C1 = 0.4758 - 0.002906T \quad -40° \text{ C} < T < 80° \text{ C}$$
$$r = -0.998$$

$$C2 = -3.3271 - 0.001175T \quad -40° \text{ C} < T < 80° \text{ C}$$
$$r = 0.785$$

$$C3 = 0.0020 - 0.0000478T \quad -40° \text{ C} < T < 80° \text{ C}$$
$$r = -0.971$$

where r is the correlation coefficient and is the measure of the goodness-of-fit of the data
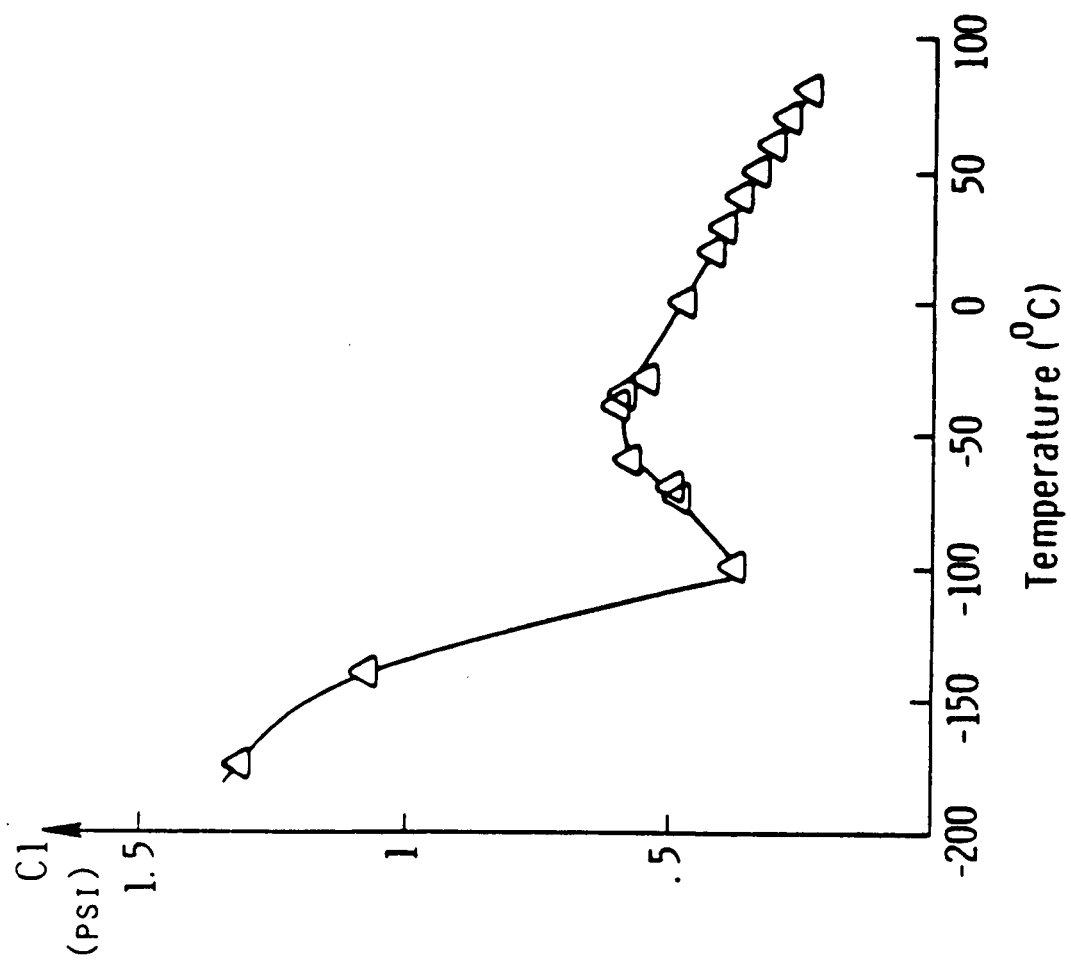
Figure 8. Plot of zero offset pressure coefficient as a function of temperature for "spider" module.
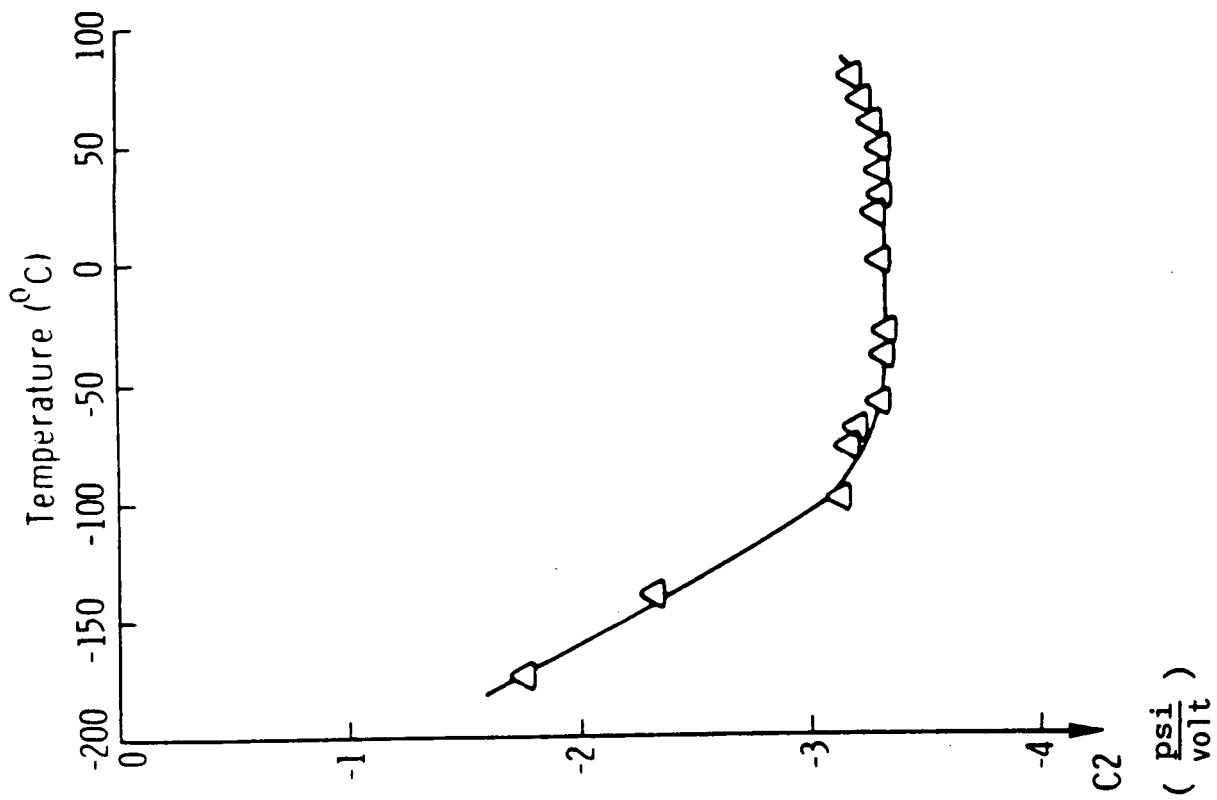
15

Figure 9. Plot of sensitivity coefficient as a function of temperature for "spider" module.
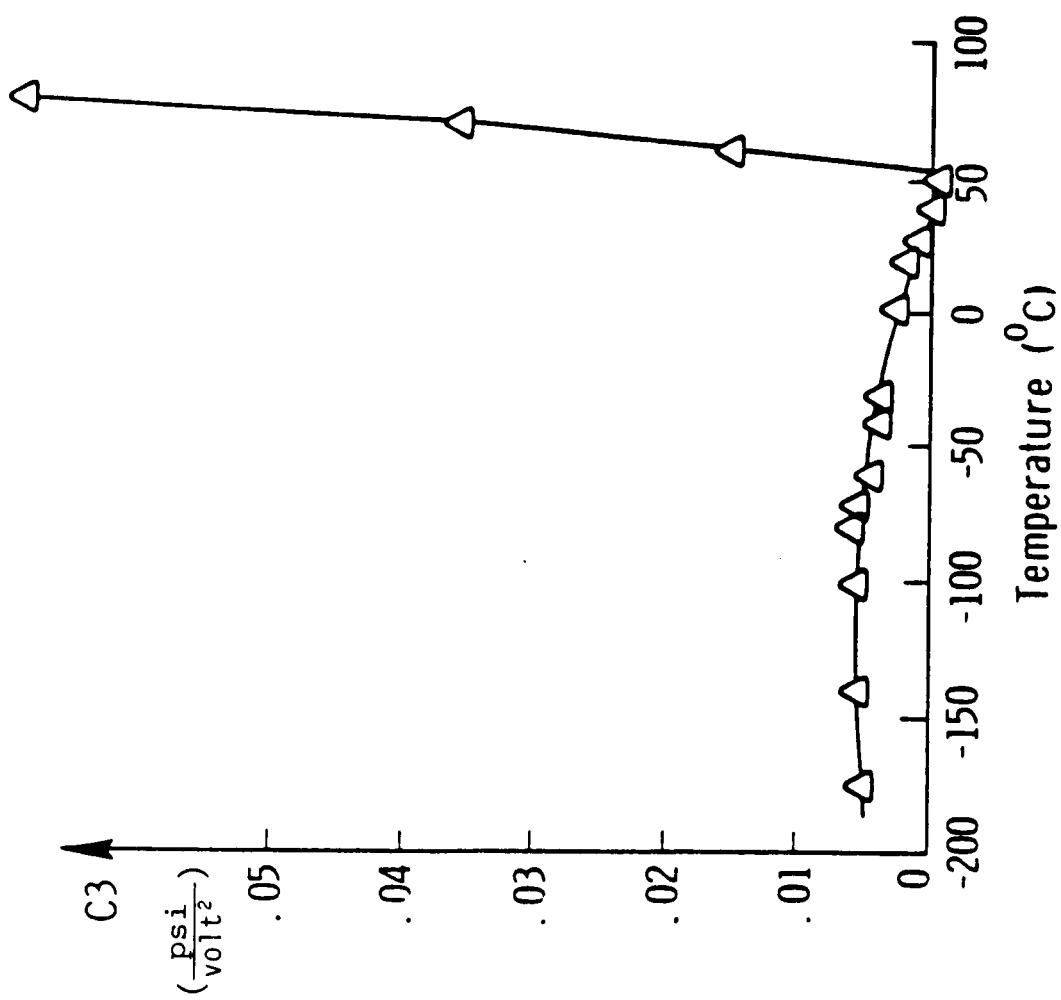
Figure 10. Plot of nonlinear coefficient as a function of temperature for "spider" module.

17

to a straight line. A value of one (plus

or minus) indicates a straight line.

The values for C1 and C3 are observed to be closely represented by a

straight line while the fit is not as good for C2. If linear regression

does not give values to a high enough degree of accuracy, it may be possible

to fit to other type curves. Another method that may be even better is to

store the data points in a table and use interpolation to get the coeffi-

cient values. To continue with the example, assume that the temperature

sensor registers a temperature of 0° C and the output voltage from the

bridge is 1.937 volts. The pressure can then be calculated from the equa-

tion:

$$P = 0.4758 - 0.002906(0) - [3.3271 + 0.001175(0)] (1.937)$$
$$+ [0.0020 - 0.0000478(0)](1.937)^2 = - 5.961 \text{ PSI}$$

The above values for temperature and voltage were taken from actual test

data at an applied pressure of -6.000 PSI. Although the calculated value is

off by approximately 0.65%, which is larger than desired, the example demon-

strates the technique. The temperature reading used in the example was

obtained from a thermocouple placed on the outside surface of the module.

In the proposed, compensated module the temperature will be measured in

close proximity to the pressure sensor and a decrease in measurement error

should result.

Evaluation of Temperature Sensors

Different techniques for measuring the temperature of the pressure

sensors were considered. Several of these were abandoned early due to obvi-

ous reasons such as size, weight, or the requirement for too many connec-

tions. Temperature sensors that were considered and tested were the thermo-

couple, the linear integrated circuit, and the temperature dependent

pressure sensor itself.

The thermocouple was used in conjunction with an integrated circuit thermocouple amplifier which has built-in ice point compensation. This was found to be the least desirable of the possibilities due to several drawbacks. The primary problem is the more complex circuitry involved. The printed circuit board would have to be redesigned to include the additional IC and there would almost certainly be contact potential error in feeding the thermocouple wire into the multiplexer. Another problem is the low-level signal generated and its inherent susceptibility to noise. In addition, the thermocouple is very non-linear and is difficult to compensate to a high degree of accuracy. Figure 11 shows a plot of the output error of the thermocouple amplifier as a function of temperature using a calibrated digital thermometer as a reference. This figure illustrates graphically the non-linearity and relatively large error that is present in this type of sensor.

Also shown in Fig. 11 is a plot of the output of the linear integrated circuit temperature transducer. The schematic shown in Fig. 12 illustrates a typical circuit for this sensor. As seen in the diagram, this unit behaves as a temperature dependent current source with a 1.0 ua/°C output. This sensor exhibits a smaller overall error and a calibration curve that is better behaved and, consequently, more easily compensated. It is also easily multiplexed by switching the sensors into a common load resistor which converts the current into a temperature sensitive voltage. In addition, the temperature transducer is available in chip form and is small enough to be bonded onto the pressure sensor bridge chip. It was originally intended to use this as a temperature measurement technique for the proposed module, however, another simpler and sufficiently accurate method was tested.
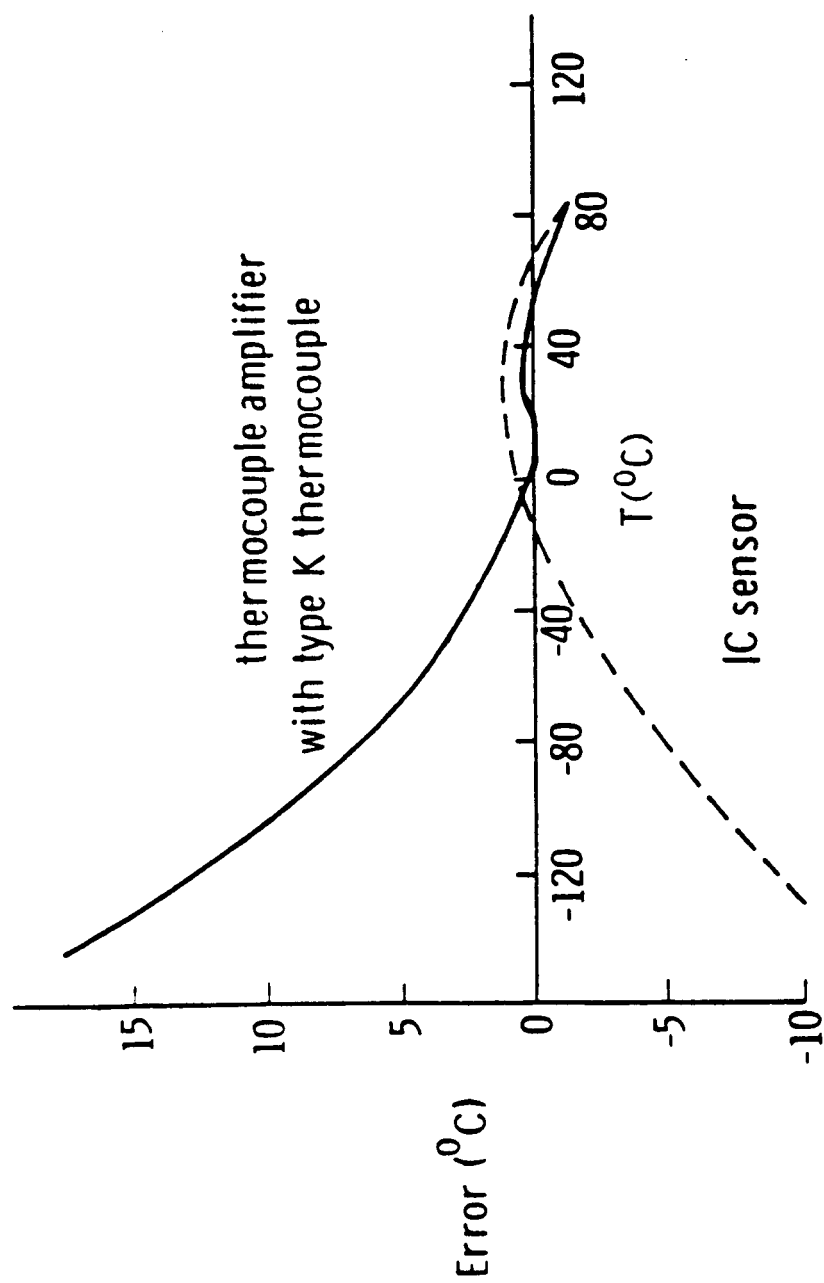
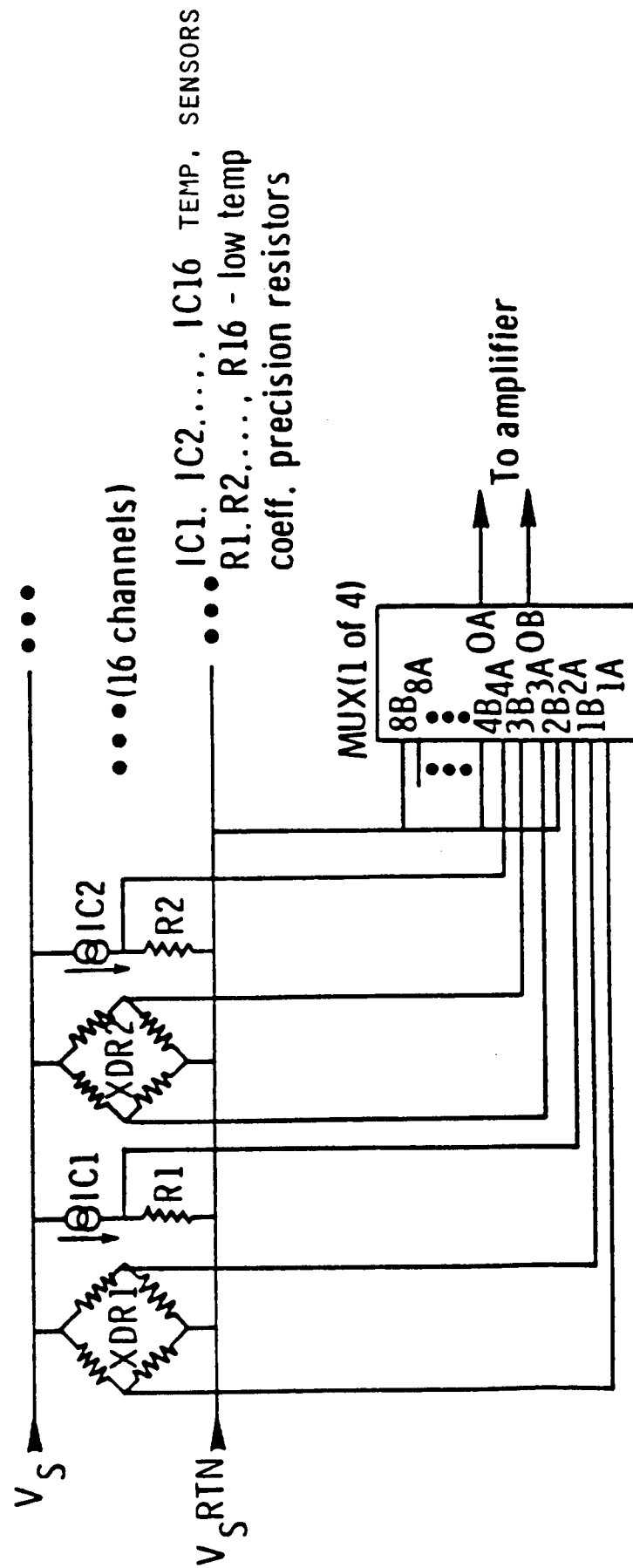Figure 11. Errors in temperature readings for thermocouple and integrated circuit type sensors.

20

Figure 12. Circuit diagram of pressure module using integrated circuit temperature sensors.

thermocouple amplifier wnicn has built-in ice point compensation. This was found to be the least desirable of the possibilities due to several drawbacks. The primary problem is tne more complex circuitry involved. Tne printed circuit board would have to be redesigned to include the additional IC and tnere would almost certainly be contact potential error in feeding the thermocouple wire into the multiplexer. Another problem is the lowlevel signal generated and its inherent susceptibility to noise. In addition, tne thermocouple is very non-linear and is difficult to compensate to a high degree of accuracy. Figure 11 shows a plot of the output error of tne thermocouple amplifier as a function of temperature using a calibrated digital thermometer as a reference. This figure illustrates grapnically the non-linearity and relatively large error that is present in this type of sensor.

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The metnod selected involved taking advantage of tne relatively large

temperature coefficients of the resistive elements that make up the semiconductor pressure sensor. By placing a low temperature coefficient precision resistor in series with the pressure transducer, an output voltage can be obtained between the resistor and the bridge which will be proportional to temperature. Figure 13 shows the basic circuit configuration and Fig. 14 is a plot of the resulting output voltage as a function of temperature. As can be seen by the diagram, this results in the simplest configuration of all and the accuracy of the sensor should be sufficient to provide the necessary compensation. The precision film-type resistors with very low temperature coefficients (in the order of 100 ppm/°C) are available in chip form and can be conveniently bonded to the substrate next to the pressure transducer. Then, during fabrication, the resistor is simply connected in series with the bridge. The value of the resistor is chosen to give a voltage on the same order of magnitude as the bridge output. The primary drawback of this configuration is the sacrifice of half of the pressure sensors. However, additional testing along with some thermal analysis will probably show that fewer temperature sensors are actually needed.

Proposed Design of the Cryogenic ESP Module

Figure 15 shows an artist's conception of the proposed ESP module. In this design it is noted that the temperature sensor is mounted directly on the pressure transducer bridge. Another technique is to mount the temperature sensor (resistor) directly on the substrate in close proximity to the bridge. Also seen in the figure is one method of heating the substrate. The control of the substrate heater is accomplished by monitoring all the temperature sensors as they are scanned and, when one indicates a temperature of less than a minimum value (e.g., -40° C), the heater circuit is

R1, R2,...R16 are low temperature coefficient, precision resistors

(16 channels)

MUX(1 of 4)

8B 8A

4B 4A OA
3B 3A
2B 2A OB
1B 1A

To amplifier

$+V_S$

$+V_S$ RTN

XDR1 XDR2 R1 R2
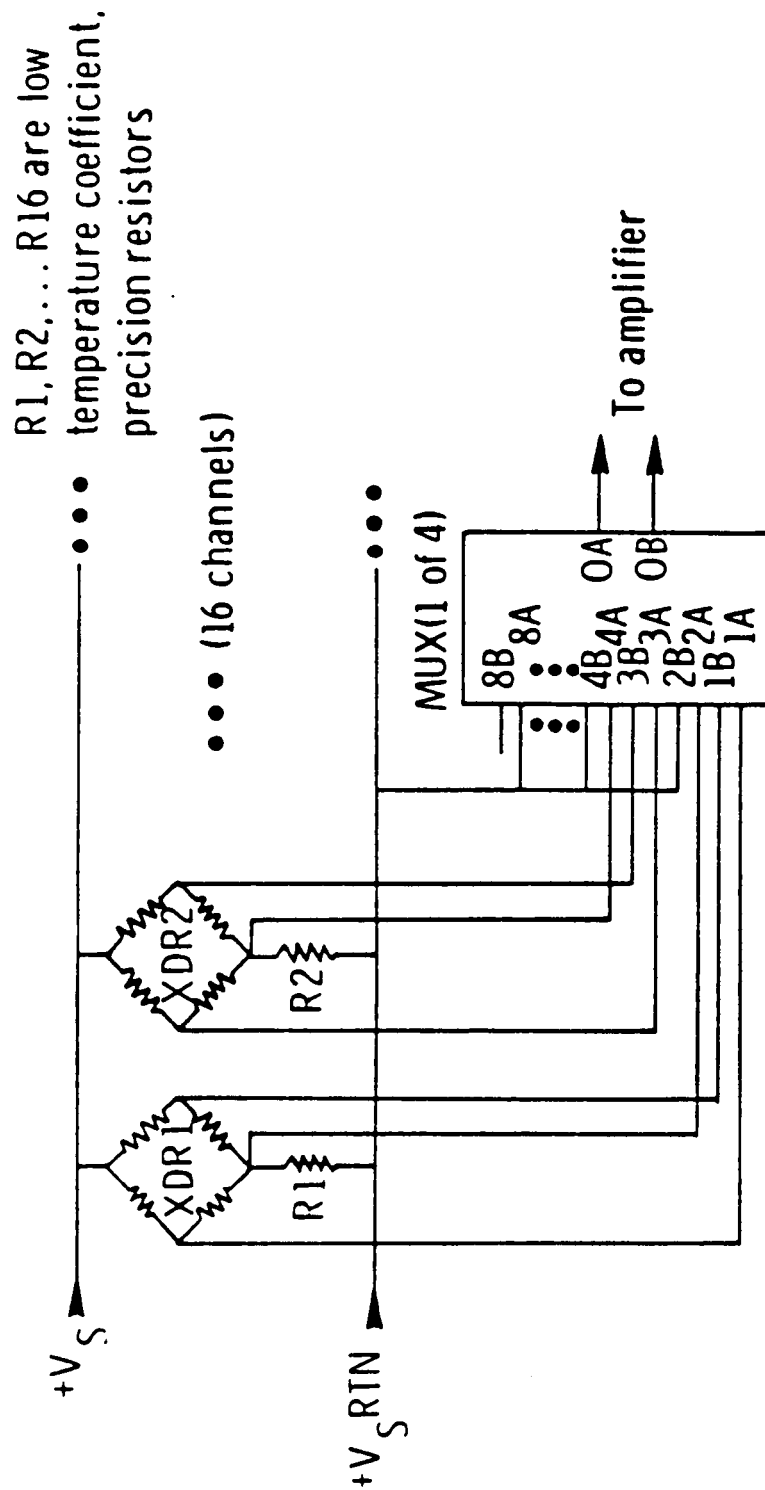
Figure 13. Circuit diagram of pressure module using variation of bridge resistance as its own temperature sensor.

Voltage
(volts)

2.3
2.2
2.1
2.0
1.9
1.8
1.7

Temperature (^{0}C)

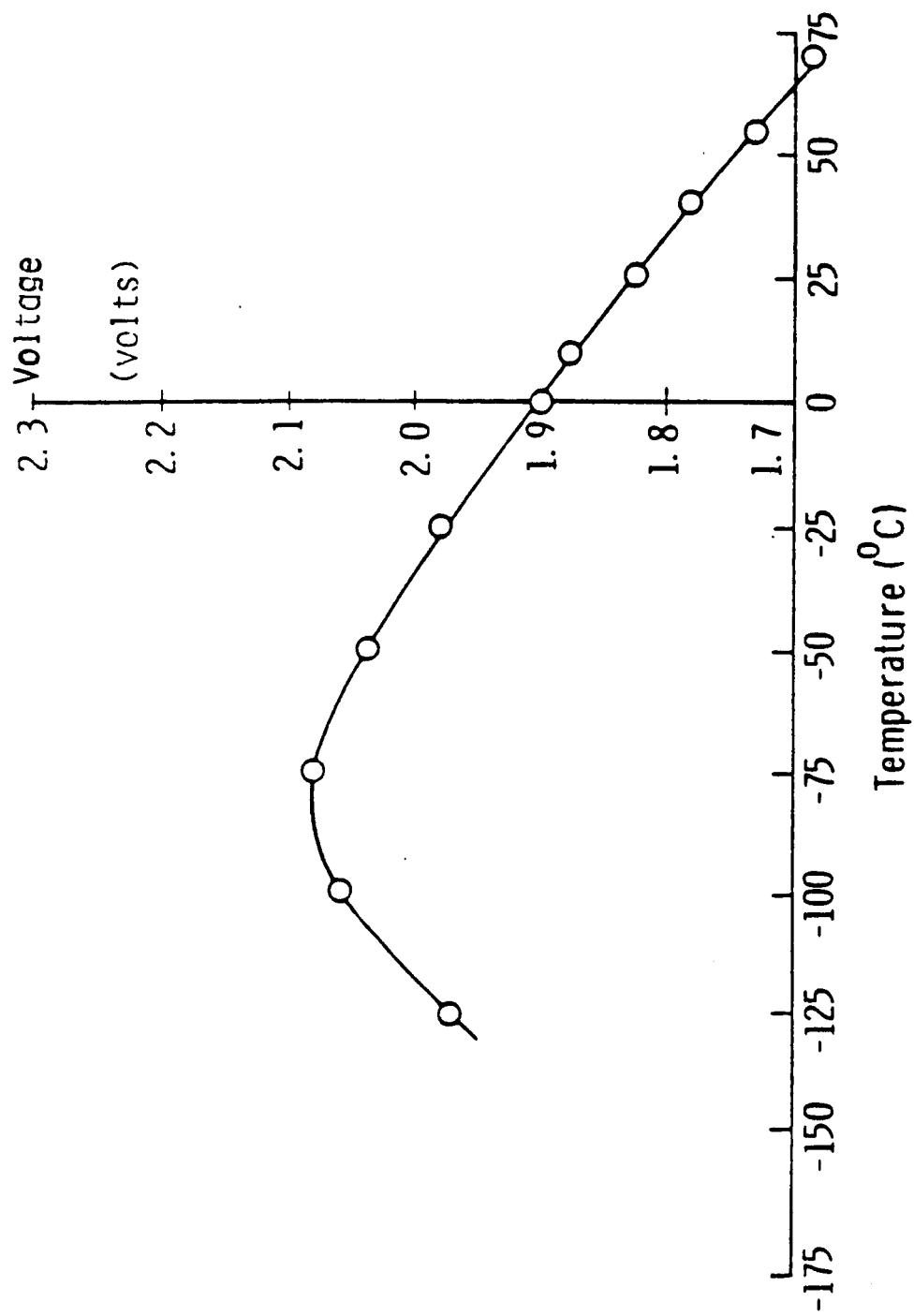-175 -150 -125 -100 -75 -50 -25 0 25 50 75

Figure 14.   Plot of output voltage as a function of temperature for
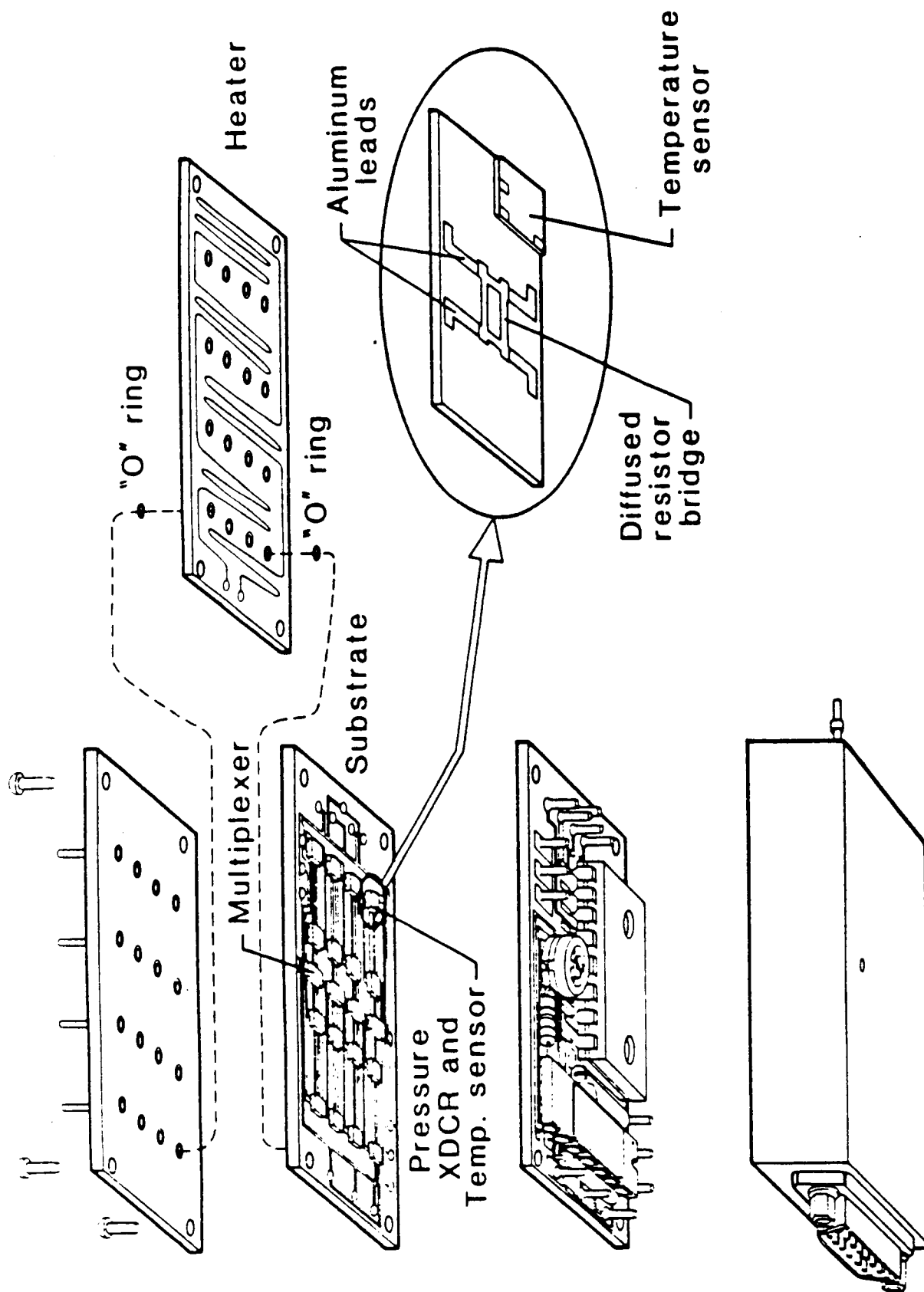bridge resistance temperature sensor.

25

Figure 15. Physical design of proposed pressure module.

26

energized. Keep in mind that the precise control of the temperature is not necessary, only the accurate measurement at each bridge location. This means that only a coarse control of the substrate temperature is required. As the data acquisition system scans the 32 channels, it will alternately take a pressure reading and a temperature reading and the values will be used to calculate the unknown pressure using the equations given earlier in this paper.

Concluding Remarks

This research has shown the feasibility of fabricating an electronically scanned pressure module to make temperature compensated pressure measurements in a cryogenic environment without the need for large heated enclosures. The characteristics of the semiconductor bridges indicate that the minimum temperature for reliable operation is about -40° C. With a combination of local substrate heating and accurate local temperature measurement, it is possible to make highly accurate pressure measurements. The sacrifice in channel capacity can most probably be offset by the strategic placement of a few temperature sensors in conjunction with the appropriate thermal analysis. All of the techniques and components required to fabricate the module are presently available.

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The units tested failed to meet accuracy specifications over the complete temperature range, which was expected. However, the sensors showed acceptable and predictable behavior over the temperature range from approximately -40°C (233 K) to 70°C (343 K). It was determined that a combination of local heating and accurate temperature monitoring can result in a device that can be compensated for temperature as well as its other physical properties. The design of a prototype for operation in a cryogenic environment is proposed, and a method for compensation is developed.

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